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FLAT KNITTING LOOP DEFORMATION SIMULATION BASED ON INTERLACING POINT MODEL

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Abstract:

In order to create realistic loop primitives suitable for the faster CAD of the flat-knitted fabric, we have performed research on the model of the loop as well as the variation of the loop surface. This paper proposes an interlacing point-based model for the loop center curve, and uses the cubic Bezier curve to fit the central curve of the regular loop, elongated loop, transfer loop, and irregular deformed loop. In this way, a general model for the central curve of the deformed loop is obtained. The obtained model is then utilized to perform texture mapping, texture interpolation, and brightness processing, simulating a clearly structured and lifelike deformed loop. The computer program LOOP is developed by using the algorithm. The deformed loop is simulated with different yarns, and the deformed loop is applied to design of a cable stitch, demonstrating feasibility of the proposed algorithm. This paper provides a loop primitive simulation method characterized by lifelikeness, yarn material variability, and deformation flexibility, and facilitates the loop-based fast computer-aided design (CAD) of the knitted fabric.

Keywords:

Flat knitting; interlacing point; loop deformation; texture mapping; loop primitives

1. Introduction

In the simulation of the appearance of the fabric, the computer graphic techniques are used to display the ideas of the designers on-the-screen quickly and intuitively [1]. The application of these techniques has the potential for improving design efficiency, reducing development cost, and increasing the enterprise productivity and responsiveness. The knitted fabric is generated by bending the yarns into the cycles and then intermeshing them. The loops take the form of the complicated 3D curves [2, 3] so that the texture at the surface is distorted and modified, and the different structure may lead to loop deformation. The loop modeling is the foundation of knitting CAD technology [4]. Loop deformation is a challenging problem, and it is also an important problem in the reality-based computer-aided design system of the knitted fabric.

Many geometrical models have been created by researchers for plain knitted fabric in the last century, including those of Peirce [5], Chamberlain [6], leaf and Glaskin [7], and Munden [8]. Existing work on loop simulation focuses on the 3D simulation of the loop. The shape of the loop in different structures has been simulated by Kurbak [9-11]. This method can accurately describe the spatial structure of the loop, however, different strategies need to be adopted for different loops. So it could not be a generic method and lacks flexibility during design. In addition, the surface of the commonly used 3D loop is smooth and it is difficult to represent the yarn hairiness [12, 13]. Simulating the fine surface of the yarn requires more running time and higher configuration of the computer. Therefore, this paper focuses on 2D simulation to produce a flexible loop model capable of representing the loop texture in a quick and lifelike manner. Additionally, it can be used as the loop primitive for CAD of the flatted knitted fabric. This paper analyzes the impact of interlacing point in the knitted fabric on loop deformation, proposes an interlacing point-based model for the loop central curve, and utilizes the cubic Bezier curve to fit the center curve of the regular loop, elongated loop, transfer loop, and irregular deformed loop. In this way, an interlacing point-based generic curvilinear function applicable to the deformed loop is obtained. The texture mapping is done on the loop with the central curve as the benchmark. Then, texture interpolation and brightness variation is applied to model the deformed loop in a lifelike manner. It supports flexible deformation and can be used as the primitive for CAD of lifelike knitted fabric.

2. Definition of the interlacing point

The points in Figure 1(a) are all interlacing points. They are the basic units for loop intermeshing. The knitted fabric is formed by intermeshing of loops at the interlacing point. A loop has two interlacing points, as shown in Figure 1(b). The red point is the interlacing point of the loop with the red line as the central curve. The point below is the starting point and the point above is the ending point. The starting point represents the location where the one or more original loops on the existing knitted fabric intermesh with existing loops when they are cleared. The ending point is formed due to the constraints of the old loops on the new loops. The ending point refers to the point that is formed when the existing loop intermeshes with the next loop when it is cleared.

Not all stitches of the flat knitted fabric have two interlacing points. The interlacing point may be missing in some cases. For example, the old loop has not been cleared completely,

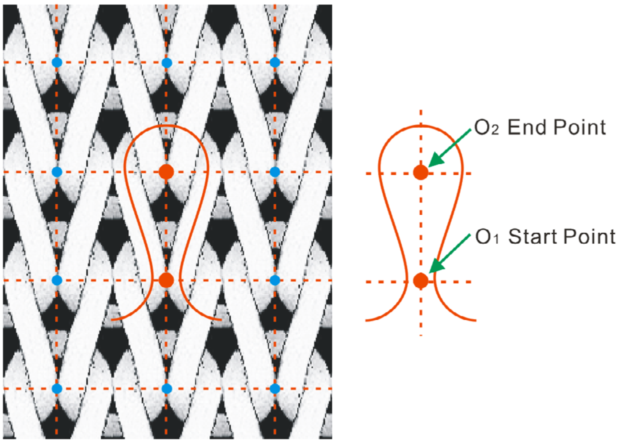


Figure 1. Interlacing point of the loop

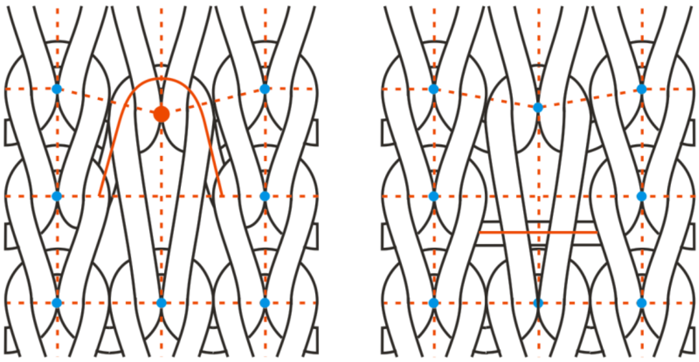
during the tuck knitting, therefore, the interlacing point of the tuck only has the starting point, as shown in Figure 2(a). While the float is being knitting, the needle does not work and the yarn does not intermesh with the loops up and down, so there is no interlacing point, as shown in Figure 2(b). Neither the tuck nor the float enables the old loop to be cleared promptly. Thus, the ending point of the old loop moves upward and the loop deforms, leading to a long loop.

The flat knitting machine can perform various actions (e.g., loop transfer and bed moving). The location of the interlacing point may be irregular. Different loop structures and diverse knitted fabric appearances are available through upward/downward and left/right movement or overlapping of interlacing points. The eyelet structure can be formed by loop transfer and bed moving of the flat knitting machine, which can lead to deviation of the ending point of the loop marked by the red line and to overlapping with neighboring loops, as shown in Figure 3(a). For the cable structure, the four neighboring loops sway their locations pairwise through loop transfer and bed moving. Due to the deformation of loops, the interlacing points of this group of loops move, thereby visible concave and convex 2*2 cable structures are formed, as shown in Figure 3(b). Deformation of the loop is more complicated than those of tuck and float. So this paper focuses on loop deformation caused by changes of the interlacing points in the loop. The force analysis of loop has not been discussed here, therefore, the physical model has not been established. The loop deformation from the angle of geometric is only studies.

3. Loop center curve fitting

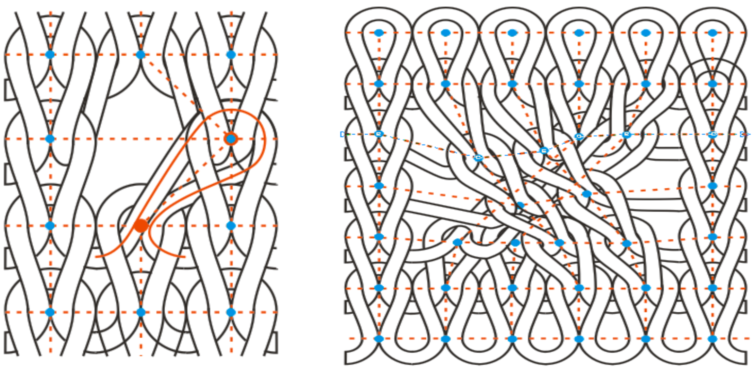
3.1 Cubic Bezier curve

The Bezier curve[14] is capable of drawing complicated curves. Given the points that can roughly outline the shape of the curve, the Bezier formula can be utilized to approximate to these points and draw the desired curve. The given points that roughly outline the shape of the curve are called as the controlling points. The Bezier curve has an endpoint property, stating that the starting and ending points of the curve is exactly same as that of the controlling points. The cubic Bezier curve based on four controlling points is commonly used. It can produce smooth curves and entails slight computational complexity. The $P(t)$ curve in the Figure 4 is formed by approximating to the four controlling points P_0, P_1, P_2, P_3. It is



(a) Interlacing point of tuck (b) Interlacing point of the float

Figure 2. Tuck and float



(a) Interlacing point in eyelet stitch (b) Interlacing point in cable stitch

Figure 3. Interlacing point in different stitches

given in Eq. (1). As this paper represents a complicated curve, each segment of the curve is designed individually and then the single parts are connected smoothly with each other. The size of loop is smaller. So keep the G^1 continuous between multiple curves, and the loop deformation can be realized in smoothness. To ensure smooth and G^1 continuous joint between *P(t)* and *Q(s)*, they need to meet the condition that the points *P2,P3=Q0,Q1* are collinear, as shown in Figure 4.

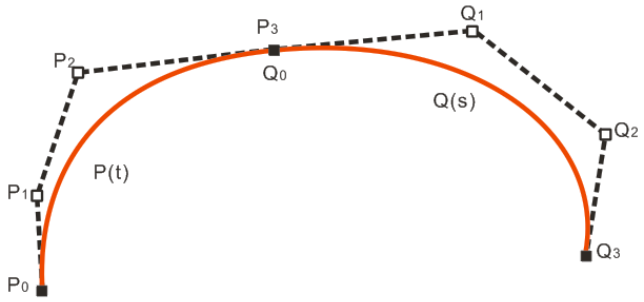


Figure 4. Two continuous cubic Bezier curves

$$P(t)=\begin{bmatrix} t^3 & t^2 & t & 1 \end{bmatrix}\begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} \qquad 0 \le t \le 1 \tag{1}$$

3.2 Regular loop center curve

As shown in Figure 5, a loop central curve can be regarded as a continuous curve obtained through concatenation of six cubic Bezier curves. Given the diameter *d* of the yarn, width *4d* and height *8d* of the loop[5], the locations of the starting point O_1 and the ending point O_2 of the interlacing point can be obtained. With O_1 as the origin of coordinates, the interlacing point can be utilized to determine the coordinates of the seven points in the curve (A_0, A_3, B_3, C_3, D_3, E_3, and F_3), and the 12 other controlling points (A_1,A_2,B_1,B_2,C_1,C_2,D_1,D_2,E_1,E_2,F_1,*F2*). We can determine the coordinate of each point, as shown in Figure 5. With the locations of these points, we can obtain six cubic Bezier curves: $\overset{\frown}{A_0A_3}$, $\overset{\frown}{A_3B_3}$, $\overset{\frown}{B_3C_3}$, $\overset{\frown}{C_3D_3}$, $\overset{\frown}{D_3E_3}$, $\overset{\frown}{E_3F_3}$. Due to collinearity of points *A2, A3, B1*, $\overset{\frown}{A_0A_3}$ and $\overset{\frown}{A_3B_3}$ are continuous. Similarly, other curved sections are continuous as well. Thus, a continuous loop central curve can be obtained. Compared with the actual loop, this model simplifies the yarn diameter changes caused by force and the 3D bending form of loop intermeshing, and this paper focuses only on the 2D yarn bending and deformation of the loop.

4. Model of Deformed Loop Center Curve Based on Variation of the Interlacing Point

4.1 Deformation of the elongated loop center curve

The elongated loop will occur in the knitted fabric if the needle of the loop is not cleared while knitting the next line. To show it visibly during design, the elongated loop will be displayed in integral multiple of the course spacing. When the loop is elongated, the *x*-coordinate of the point O_2 remains constant but the *y*-coordinate increases. Figure 6 shows the deformation of a loop central curve, which is elongated by a course spacing. For the controlling points near the ending point, their vertical coordinates increase by a course spacing, and their abscissas remain the same.

4.2 Deformation of the transfer loop central curve

The transfer loop is common in the fashioned knitting and eyelet structure. The horizontal displacement of the ending point causes deformation of the loop. As shown in Figure 7, the loop drifts to the right by 1 needle, the point O_2 drifts to the neighboring loop, and O_1O_2 is no longer a vertical segment. Four endpoints (A_0,A_3,E_3,F_3) near the starting point O_1 remain the same. And $B_3D_3 \perp O_1O_2$, C_3 is in the extended line of O_1O_2, $O_2B_3=O_2C_3=O_2D_3=3d/2$, $A_2B_1 \| F_1E_2 \| B_2C_1 \| E_1D_2 \| O_1O_2$,$D_1C_2 \perp O_1C_3$, $A_2A_3=E_3F_1=3d/4$, $A_3B_1=E_3E_2=B_2B_3=D_3E_1=d$. With these controlling points, the transfer loop center curve is determined.

4.3 Deformation of the irregular deformed loop center curve

The upward/downward and left/right displacement of the interlacing point in the loop is not necessarily an integral multiple of the course spacing or wale spacing. Additionally, the upward/downward displacement and the left/right displacement may occur at the same time. This deformation is called irregular deformation. Figure 8 shows the movement of each point for irregular loop deformation.

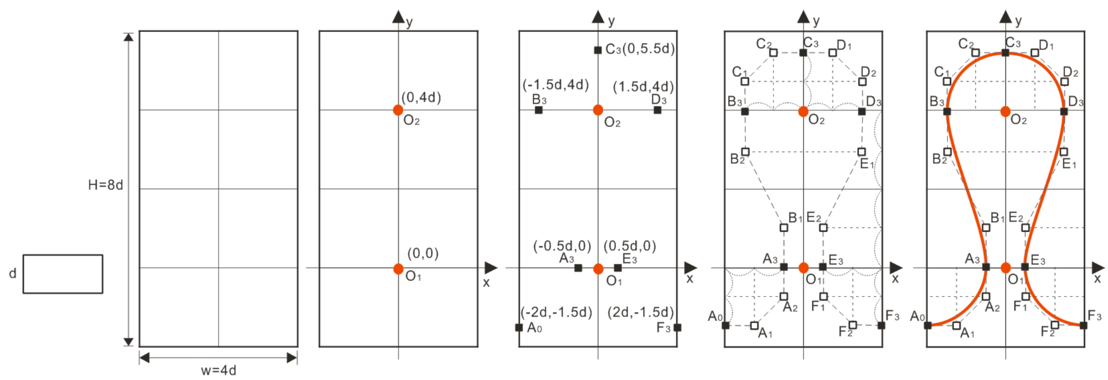


Figure 5. Regular loop central curve

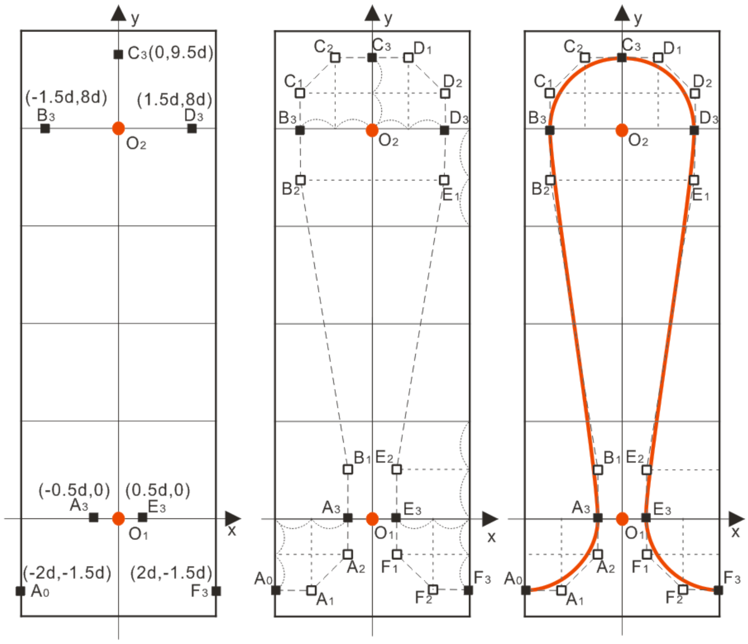


Figure 6. Elongated loop central curve deformation

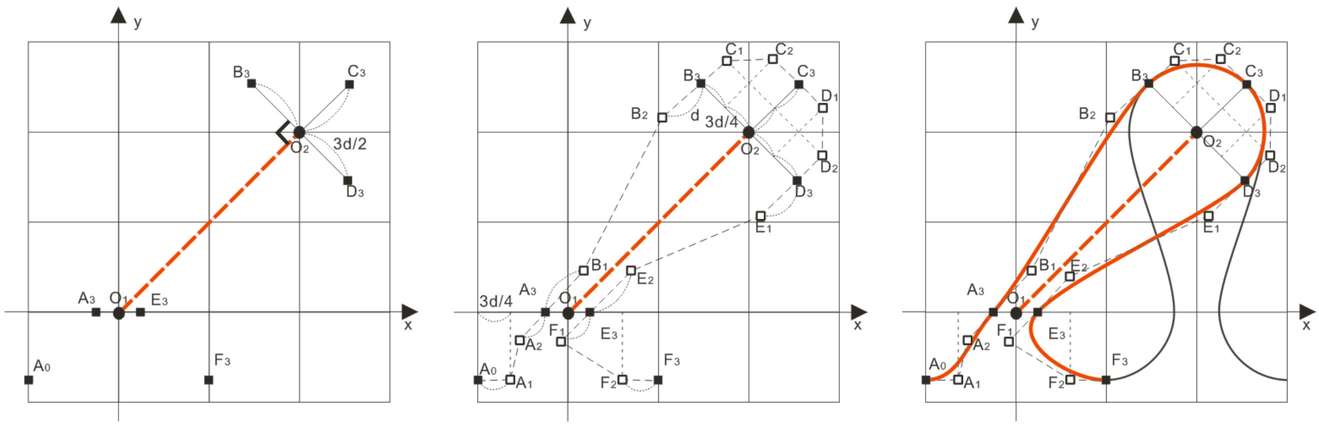


Figure 7. Transfer loop central curve deformation

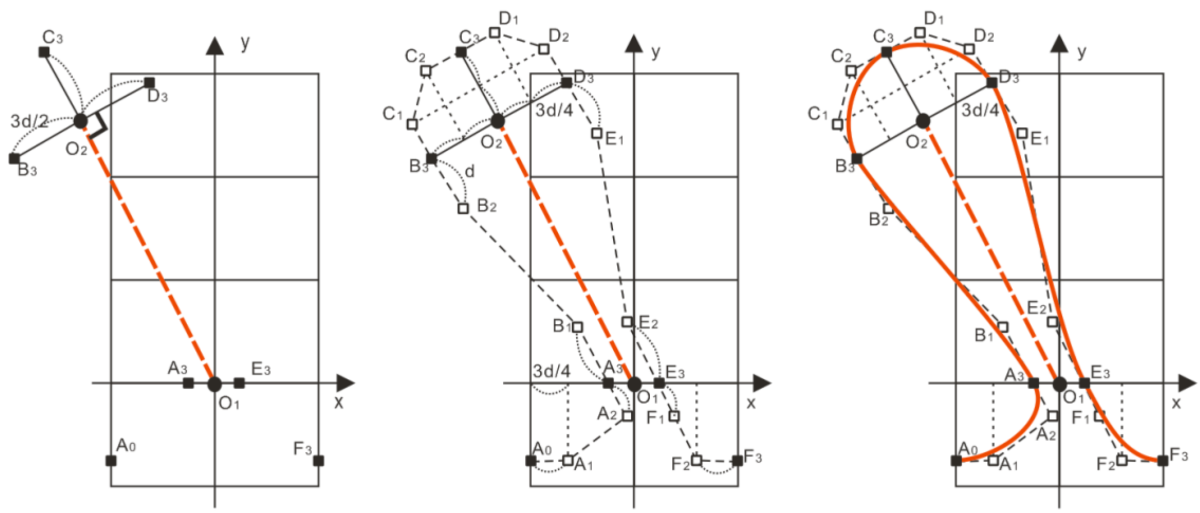


Figure 8. Irregular deformed loop central curve deformation

4.4 Model of the deformed loop center curve

From the above analysis, it can be observed that Figure 8 provides a generic deformation method for the loop central curve. It encompasses the traditional loop and several regular deformations. Thus, a generic interlacing point-based model for the deformed loop center curve can be constructed. To facilitate program implementation in the computer, the curvilinear equation of $\overset{\frown}{A_0 A_3}$ can be written as Eq. (2), where *Ax(t)* and *Ay(t)* denote the horizontal and vertical coordinates of the point in the curve. A_{0x}, A_{1x}, A_{2x}, A_{3x}, denote the horizontal coordinates of points A_0, A_1, A_2, A_3, A_{0y}, A_{1y}, A_{2y}, A_{3y} denote the vertical coordinates; t ranges from 0 to 1. Its increment can be designed based on the length of the curve. Other five curvilinear equations can be obtained similarly.

$$\begin{cases} Ax(t) = (1-t)^3 A_{0x} + 3t(1-t)^2 A_{1x} + 3t^2(1-t)A_{2x} + t^3 A_{3x} \\ Ay(t) = (1-t)^3 A_{0y} + 3t(1-t)^2 A_{1y} + 3t^2(1-t)A_{2y} + t^3 A_{3y} \end{cases} \quad 0 \le t \le 1 \tag{2}$$

5. Loop Texture Simulation and Optimization

After the deformed loop central curve is obtained, this curve can be defined as the benchmark to simulate the loop using the real-world yarn texture. In the experimental results given below, the yellow point is the interlacing point, the red point is the endpoint of the curve, and the green point is the controlling point.

5.1 Yarn texture-based simulation

The yarn texture is cyclical. The corresponding yarn texture can be observed using the length of the curve. The column-wise texture mapping [15] is done in the normal direction on each pixel point in the curve. In Figure 9, *L* denotes the total length of the yarn texture, and L_0 is the corresponding length that a point in the curve has in the yarn texture. The *RGB* values of all pixel points in the column can be obtained in this way. The pixel points in the central line of the yarn correspond to the points in the loop center line. Other points are arranged one by one on both sides of the normal line, finally yielding the texture mapping results on the right side.

5.2 Loop texture interpolation

The experimental results show that due to errors in the computed length and the pixel points and to the unsmoothness of the curve, some texture may be missed during column-wise texture mapping to make the produced loop incomplete [16]. Interpolation on the texture is required to be performed during texture mapping to increase the continuity of the texture. The four-point interpolation method is adopted in this paper, as shown in Figure 10. In this method, during texture mapping, the value assigned to a point is also assigned to the four neighboring points. Despite the increase in computational complexity, this method can effectively reduce the missing of texture, producing smoother and more continuous loops.

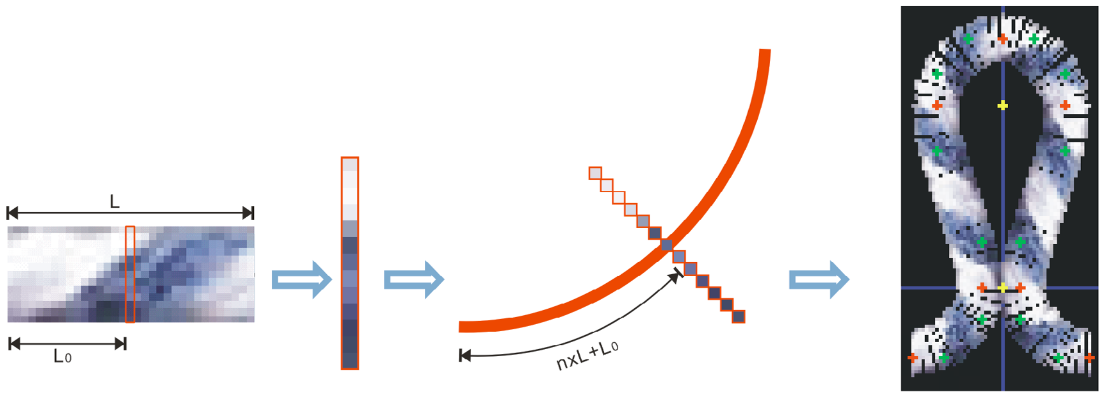


Figure 9. Texture mapping based on central curve

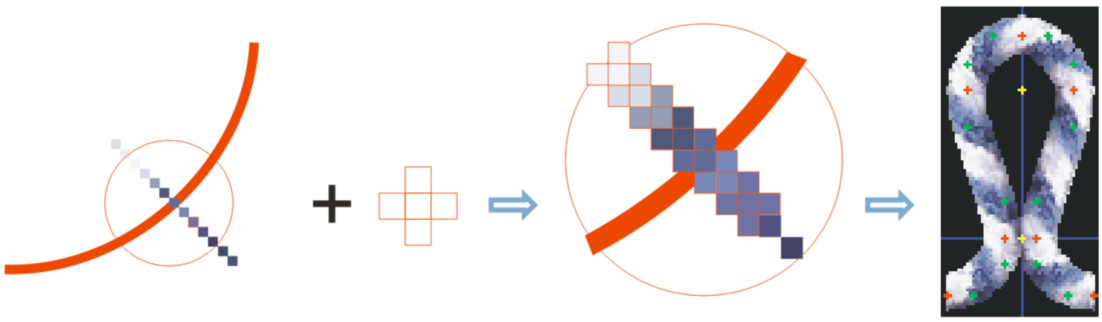


Figure 10. Four-point texture interpolation

5.3 Loop texture optimization

The surface of the loops that have been subjected to texture mapping has the same brightness. So, brightness variation is introduced to make it more lifelike. The *LAB* color space[17] is used for brightness variation. The *RGB* value of the loop is converted to the *LAB* value. After being multiplied by a height-related brightness coefficient, the value of *L* is then converted to the *RGB* value. The brightness variation coefficient of the face loop can be computed as:

$$L_f = L_0 + \frac{L_{max} - L_0}{2} - \frac{L_{max} - L_0}{2}\cos\left(h \times \frac{2\pi}{H}\right) \quad 0 \le h \le H \quad (3)$$

where *Lf* is the brightness coefficient of the loop at the current height, *L0* is the original brightness coefficient, *Lmax* is the maximum brightness coefficient, *h* is the current height, and *H* is the total height of the loop. The optimized texture is shown in Figure11(c).

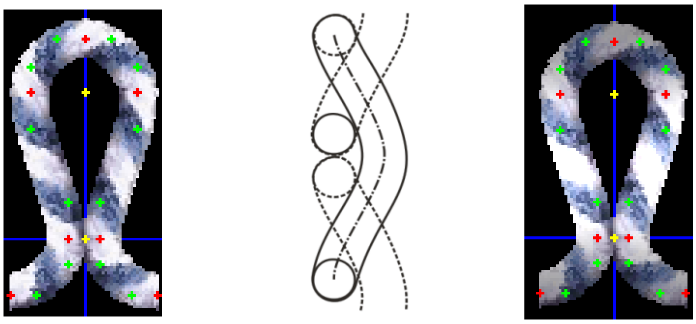
6. Deformed Loop Simulation

6.1 Simulation algorithm for the deformed loop

The computation methods above are implemented through computer programs. Figure12 presents the steps of the algorithm for a deformed loop.

6.2 System interface

The loop deformation program *LOOP* is developed based on the algorithm steps above in VC++. Figure 13 shows the application's interface. The yarn texture can be imported to the application. Then, the system will automatically determine the diameter of the imported yarn texture. Taking pixel as the unit, the system computes the width and height of the regular loop. The default action and the display scale are loop formation and 100%, respectively. The starting point *O1* and ending point *O2* of the traditional loop are shown in the interlacing point below. There are five options for brightness, where 0 implies



(a) Without brightness change (b) Side view of loop combination (c) Add brightness change

Figure 11. Face loop texture optimization

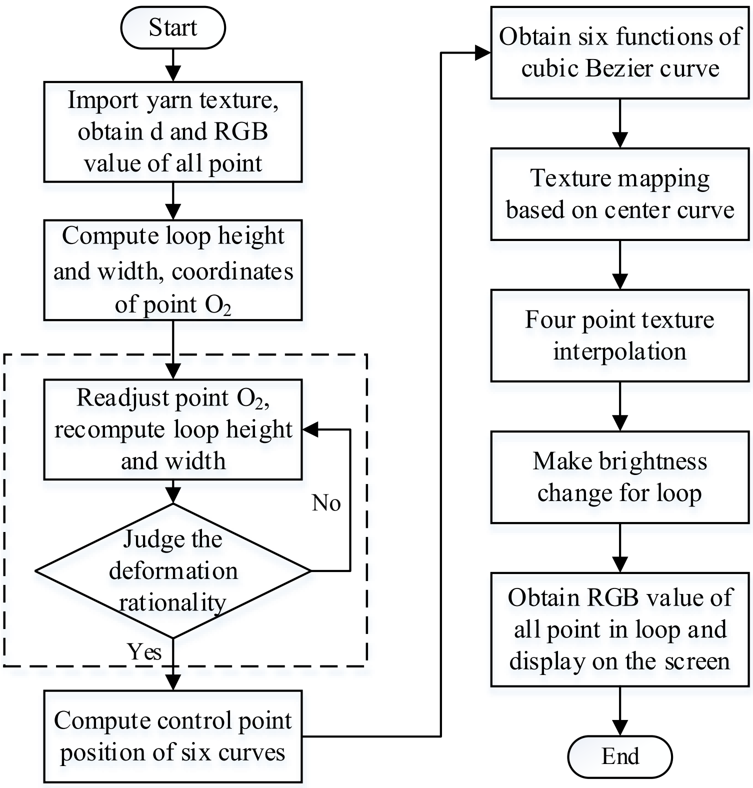


Figure 12. Algorithm flow chart

no variation, 1 implies the face loop brightness mode, 2 implies the back loop brightness mode, 3 implies the *face loop turn to back* brightness mode, and 4 implies the back loop turn to face brightness mode. The right region shows the simulated loop. Loops with different shapes can be displayed by adjusting the location of the interlacing point.

6.3 Experimental verification

To verify feasibility of the proposed methods, the normal loop, elongated loop, transfer loop and irregular loop have been simulated using three different yarn textures, respectively. The experimental results are shown in Table.1.

By analyzing the results above, the model is not restricted by yarn texture and shape of loop, it can be simulated in a continuous and deformed texture. Through the change of surface brightness, 3D effect is formed through the 2D graphics. It is proved that the model of higher flexibility, better reality, is a rapid and effective method for generation of loop primitive.

6.4 Practical applications

The cable structure is very common in the flat-knitted fabric. Because bed moving and loop transfer can deform the loop, each deformed loop is simulated via *LOOP* and the texture sample No.2. Table.1 lists the primitives of the deformed loop and the location of *O2*. Based on the method in Fig.14 (a), they can be combined to form the cable structure in the CAD application, as shown in Figure 14(b). It has the ability to authentically capture loop deformation and the connection between loops, which enable designers to observe intuitively.

When the loops are combined into a stitch, it is an ideal presentation mode, different from real fabric, the deformation is restricted to a limited range, and the connection between the loops is relatively loose. Although it is reduced in the sense of reality, it can be more clearly than the real fabric in the observation of the connection between the loops.

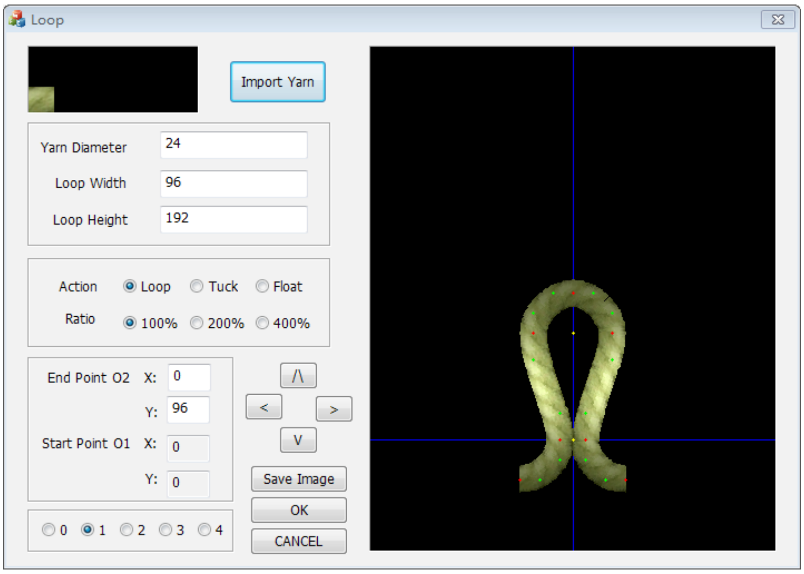
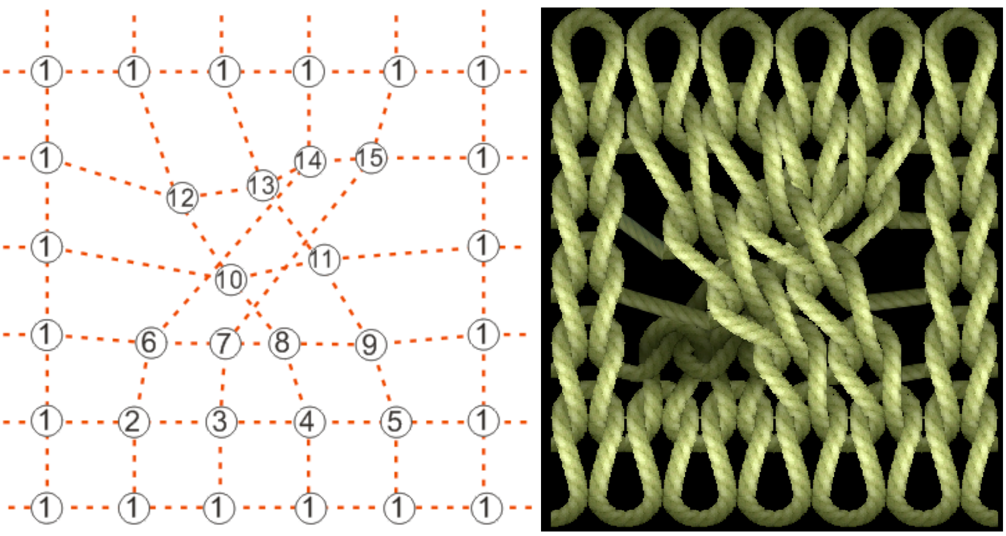


Figure 13. Loop interface



(a) Combined frame diagram (b) Loop combination

Figure 14. Cable stitch simulation

Table 1. Deformed loop simulation with different textures

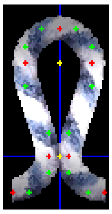
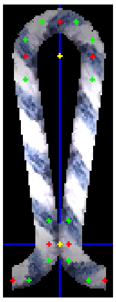
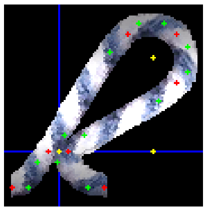
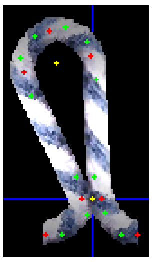
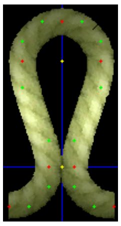
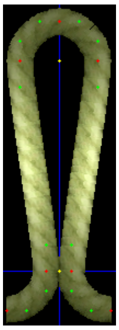
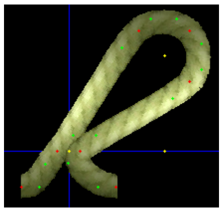
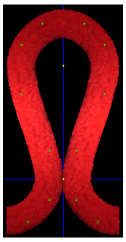
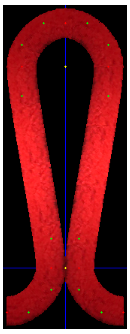
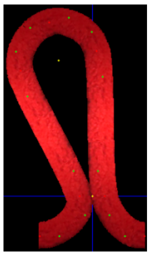
Sample No.	Regular loop	Elongated loop	Transfer loop	Irregular deformed loop
Sample 1  Double color yarn *d*=13*pt*				
	$O_2(0,52)$	$O_2(0,104)$	$O_2(52,52)$	$O_2(-20,80)$
Sample 2  Twisted yarn *d*=24*pt*				
	$O_2(0,96)$	$O_2(0,192)$	$O_2(96,96)$	$O_2(-35,120)$
样本3  Fluffy yarn *d*=39*pt*				
	$O_2(0,156)$	$O_2(0,312)$	$O_2(156,156)$	$O_2(-60,250)$

Table 2. Deformed loop primitives of cable stitch (*d*=24*pt*)

1	2	3	4	5	6	7
						
$O_2(0,96)$	$O_2(17,86)$	$O_2(4,86)$	$O_2(-28,86)$	$O_2(-28,86)$	$O_2(175,200)$	$O_2(161,202)$

8	9	10	11	12	13	14	15
							
$O_2(-61,72)$	$O_2(-54,95)$	$O_2(-56,89)$	$O_2(-64,80)$	$O_2(-47,137)$	$O_2(-46,123)$	$O_2(0,98)$	$O_2(27,96)$

7. Conclusion

This paper proposes a method to deform the loop central curve through the interlacing point of the flat-knitted fabric. And the loop is simulated via texture mapping. Experiments demonstrate the ability of the proposed method to flexibly deform lifelike loop with a continuous texture. The proposed method forms the foundation for design of primitive of the knitted fabric loop. The innovation lies in this: The concept of interlacing points is put forward, loop deformation is realized by two points, and a generic deformation method for the loop central curve is proposed.

(1) The definition, function, and variation pattern of the interlacing point in the knitted fabric loop are analyzed. The coordinates of the interlacing point are utilized to yield the seven endpoints in the loop central curve and 12 controlling points. The loop central curve is partitioned into six continuous cubic Bezier curves. The loop central curves of the regular loop, elongated loop, transfer loop, and irregular deformed loop are fitted to establish a generic loop center curve model for the deformed loop.

(2) A method capable of loop simulation based on real-world yarn texture is proposed. Texture mapping is done with the loop central curve as the benchmark. The four-point interpolation and brightness variation are utilized to make the simulated loop more lifelike.

(3) The loop simulation program *LOOP* is developed using the above algorithms. Different deformed loop structures are simulated using different yarn textures. Experimental results demonstrate the effectiveness of the proposed algorithms in simulating deformed loops with diverse yarns.

(4) The deformed loop is applied to design the cable structure. In addition to making it more real, the deformed loop can clearly capture the connection between loops in the cable structure, fulfilling the requirement of designing the knitted fabric through the loop.

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